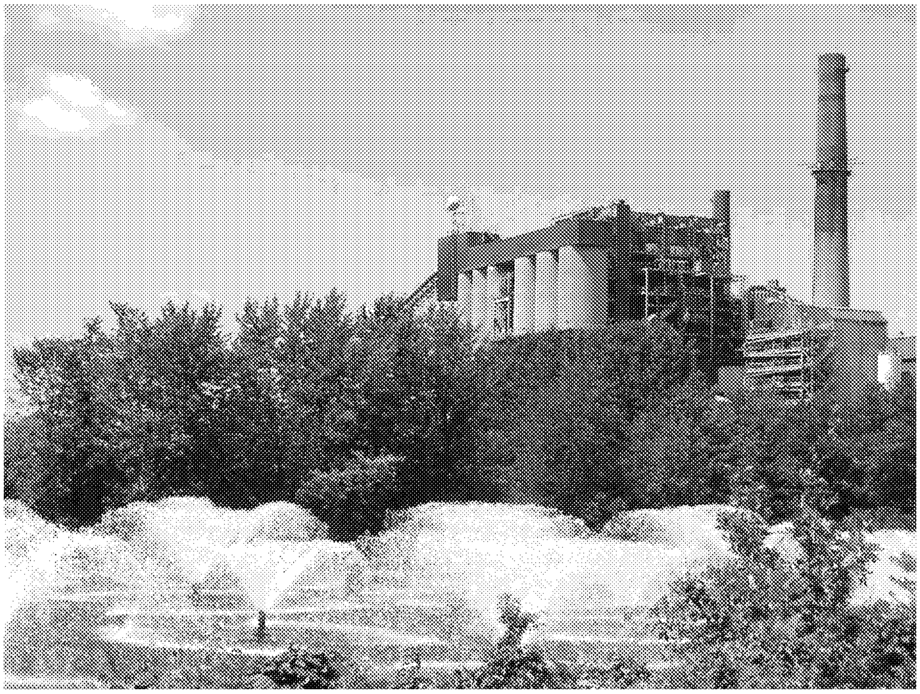
CFD Thermal Plume Modeling Technical Report

PSNH Merrimack Station Units 1 & 2
Bow, New Hampshire



PREPARED FOR
PUBLIC SERVICE COMPANY OF NEW HAMPSHIRE
D/B/A EVERSOURCE ENERGY

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1 Introduction and Purpose

Public Service Company of New Hampshire ("PSNH") operates Merrimack Station (the Station), located in Bow, New Hampshire. Merrimack Station is the largest of PSNH's fossil-fueled power plants, and has a total electrical output of approximately 480 MW. Merrimack Station operates two steam electric generating units (Unit 1 and Unit 2) and two combustion turbines. Unit 1 began operating in 1960 and has a rated production of 108 MW, while Unit 2 began operating in 1968 and has a rated production of 330 MW (Reference 6.8, Page 1).

Several engineering and biological assessments have been prepared by Enercon Services, Inc. (ENERCON), Normandeau Associates, Inc. (Normandeau), AST Environmental (AST), and LWB Environmental Services (LWB) and submitted by PSNH to the United States Environmental Protection Agency (EPA) to respond to EPA's requests for certain technology and fisheries information to support development of a new permit for the Station.

The purpose of this technical report is to document the analysis that was performed to characterize the extent of the thermal plume at sampling station S4 in the Merrimack River during various winter months of interest. This thermal assessment was performed by using the FLOW-3D® Computational Fluid Dynamics (CFD) modeling software to quantify the size, location, and extent of thermal plumes that develop when the plant is operating at design conditions for the winter months of December, January, February, and March.

Computational fluid dynamics utilizes numerical analysis of the governing equations of fluid dynamics – mass, momentum, and energy balance – to simulate the interaction of liquids and gases with surfaces defined by boundary conditions. The resolution of the CFD model is based on the number of cells or nodes (the mesh density) used to conduct the analysis. As the number of cells is increased, the resolution of the model is increased and the detailed flow patterns around smaller changes in river bathymetry are better captured. Reducing the overall area analyzed within the model domain allows the use of a higher cell density in the analysis to increase the resolution. When performing CFD analyses, the increase in the resolution of the results must be balanced with the increased computational time and cost associated with higher cell counts. The goal when generating a mesh is to develop a model that adequately represents the flow conditions and produces results to the level of resolution necessary to draw accurate conclusions, but does not require an unacceptably high computational time.

The CFD evaluation was performed using FLOW-3D® Version 10.1 which is a commercially available general-purpose computer code for modeling the dynamic behavior of liquids and gasses influenced by a wide variety of physical processes. The program is based on the fundamental laws of mass, momentum, and energy conservation. It has been constructed for the treatment of time-dependent multi-dimensional problems, and is applicable to most flow processes.

The CFD analysis included four different cases which characterized the thermal plume in the Merrimack River with the plant operating at design conditions for the four winter months of December, January, February, and March. These four winter months were selected because they are of particular biological significance with regards to the survival of the Asian clam. In order to assess these four cases, historical ambient data from the most recent six-year period of data available was used and averaged over the six-year time frame to develop average values for the given month. The six-year range provides a representative data set which fully encompasses a 5-year NPDES permit renewal cycle.

The purpose of this analysis is to characterize the thermal plume at sampling station S4 in the Merrimack River for each of the four cases described above. In order to do this, design plant operational discharge parameters were used in conjunction with historical ambient conditions to inform the input parameters to the CFD model, providing a plume characterization for design plant operation in historical winter month conditions. The purpose of this characterization is to act as a screening tool that can be used in the biological evaluation provided by AST (Reference 6.1) to determine if further analysis for any of the cases is required.

2 Case-Dependent Model Parameters

Both the effluent and the ambient conditions affect the mixing in the CFD model and can impact the predicted thermal plume. Many of the conditions, such as geometry, remain constant for all cases considered. However, several of the effluent and ambient parameters required for the CFD model vary at Merrimack Station based on the winter month being considered. These parameters include ambient river flow rate, air temperature, wind speed, and wind direction.

To account for the variability in these parameters, four cases were developed to model the thermal plume during each of the four months of interest. Case 1 assesses plume behavior using average ambient conditions for the month of December, Case 2 uses average ambient conditions for the month of January, Case 3 uses average ambient conditions for the month of February, and Case 4 uses average ambient conditions for the month of March. These four months were recommended by AST for analysis to support the biological evaluation of the Asian clam's presence in Hooksett Pool (Reference 6.1).

To analyze these four cases, values for the variable parameters listed above were averaged across the most recent six-year range of complete data available. This was done for each month of interest, creating an overall average for each parameter, for each case. These overall monthly averages are presented in Table 1. The explanations and sources for each parameter are provided in detail in Sections 2.1 through 2.4.

Table 1: Case-Dependent Model Parameters

Case	Month	River Flow (cfs)	Air Temperature (°F)	Wind Speed (mph)	Wind Direction (degrees)[1]
1	December	6,030	31.5	4.8	145.9
2	January	4,405	23.9	5.9	164.9
3	February	3,158	24.2	6.5	162.7
4	March	6,545	33.9	6.9	176.8

2.1 River Flow Rate

The daily average Merrimack River flow rate values at Merrimack Station were provided by PSNH for years 1984-2015 in Reference 6.2. These flow values were taken upstream from the Goffs Falls United States Geological Survey (USGS) gage. The flow values were corrected by Normandeau for Merrimack Station in order to accurately reflect the ambient river flow at the plant. As described above, all of the daily values in the month of interest were averaged across the most recent six-year range of complete data available (2010-2015) to create an overall average for that month's case.

[1] Wind direction is reported using a 360-degree compass indicating the direction from which the wind was blowing with respect to true north. See Section 2.4 for more details.

2.2 Air Temperature

Hourly averages of air temperature for years 2011-2016 were taken from Reference 6.3, which was ordered and downloaded from the National Oceanic and Atmospheric Administration (NOAA) database. These air temperature measurements were taken at Concord Municipal Airport, which is the closest location to Merrimack Station that reports quality controlled air temperature. As described above, all of the hourly values in the month of interest were averaged across the most recent six-year range of complete data available (2011-2016) to create an overall average for that month's case.

2.3 Wind Speed

Hourly averages of wind speed for years 2011-2016 were taken from Reference 6.3, which was ordered and downloaded from the National Oceanic and Atmospheric Administration (NOAA) database. These wind speed measurements were taken at Concord Municipal Airport, which is the closest location to Merrimack Station that reports quality controlled wind speeds. As described above, all of the hourly values in the month of interest were averaged across the most recent six-year range of complete data available (2011-2016) to create an overall average for that month's case.

2.4 Wind Direction

Hourly averages of wind direction for years 2011-2016 were taken from Reference 6.3, which was ordered and downloaded from the National Oceanic and Atmospheric Administration (NOAA) database. These wind direction measurements were taken at Concord Municipal

Airport, which is the closest location to Merrimack Station that reports quality controlled wind direction. Wind direction was reported using a 360-degree compass indicating the direction from which the wind was blowing with respect to true north (Reference 6.4). For example, a wind direction of 180° would indicate a wind blowing from due-south, towards true north. As described above, all of the hourly values in the month of interest were averaged across the most recent six-year range of complete data available (2011-2016) to create an overall average for that month's case.

3 Constant Model Parameters

A few model parameters required for the CFD model remain constant for all four cases. A summary of the constant model parameters is provided in Table 2 and detailed descriptions of each parameter are shown in Sections 3.1 through 3.3.

Table 2: Summary Table of Constant Model Parameters

Parameter	Value
Ambient River Temperature	33°F
Discharge Flow Rate	443.4 cfs
Discharge Temperature	53.6°F

3.1 Ambient River Temperature

Typically, temperature readings from the probes at sampling station N10, upstream of the Merrimack Station intake and discharge locations, would be used to inform the ambient river temperature input for the CFD model. However, during the winter months of interest (Dec., Jan., Feb., and Mar.), the temperature probes at N10 are removed from the river to avoid potential damage from icing. Therefore, historical data for the ambient river temperature during the winter months of interest is not readily available, and an assumption must be made to perform the CFD analysis.

Based on anecdotal reports, the Merrimack River has been observed to partially ice over during the winter months. Under these conditions, portions of the river would freeze into solid ice at the top of the river, while liquid water continues to flow underneath the ice, maintaining continuous river flow. Therefore, the coldest that the liquid portion of the river could theoretically be under these conditions would be 32°F, which is the coldest temperature the liquid portion of a water/ice slurry can physically be during a phase change (i.e. the liquid phase of the river freezing into ice or the ice phase of the river melting into liquid). Although the theoretical lowest temperature of the liquid portion of the river under these circumstances is 32°F, it is likely that, in reality, the flowing river is not a perfectly mixed liquid/ice slurry and the liquid portion of the river is slightly warmer 32°F, particularly towards the bottom of the river water column where there is a large gap between the water and the ice.

Therefore, to characterize the thermal plume under the river conditions described above, it was assumed that the ambient river temperature was 33°F for all four cases. A temperature of 33°F, slightly above the freezing temperature of 32°F, was selected to avoid unnecessary complications within the model that could result in inaccurate results. If the ambient temperature were set to 32°F, then any loss of energy from a single cell would result in the software considering that cell to be a solid during the next time-step. This could result in pockets of solid ice throughout the river, not only on the surface, which would significantly increase the complexity and solving time of the model and would not be representative of reality. Additionally, as described above, the flowing river is not a perfectly mixed liquid/ice slurry, and it is likely that most of the liquid is slightly warmer than 32°F and not undergoing continuous phase changes between liquid and solid.

3.2 Discharge Flow Rate

To characterize the thermal plume during a "plant on" scenario, where both Merrimack Station Units 1 and 2 are operating at design conditions, the discharge flow into the cooling canal was assumed to be equal to the combined design intake flows of the two units. The design circulating water (CW) intake flow for Unit 1 is 59,000 gallons per minute (gpm) and the design CW intake flow for Unit 2 is 140,000 gpm (Reference 6.5, Page 9). These two flow rates combine to a total design intake flow of 199,000 gpm, or approximately 443.4 cubic feet per second (cfs). Therefore, for the CFD analysis, the plant flow into the discharge canal was assumed to be 443.4 cfs for all four cases.

3.3 Discharge Temperature

The temperature of the plant's discharge flow as it interacts with the Merrimack River is primarily a function of three factors:

1. The ambient temperature of the cooling water withdrawn from the river
2. The heat load applied to the cooling water as it passes through the plant
3. The amount of cooling that occurs as the flow travels through the length of the discharge canal, prior to mixing with the ambient river flow

As described above, the ambient temperature of the river water is assumed to be 33°F for all four cases. Additionally, since all four cases are evaluating "plant on" scenarios, with both units operating at design conditions, the heat load applied to the water will be the same for all four cases. Finally, because the Power Spray Modules (PSMs) only operate under specific thermal conditions and would most likely not be in operation during the winter months of interest, the amount of cooling that occurs as flow travels through the length of the discharge canal is primarily a function of the time it takes to reach the river. The ambient air temperature and wind speed also affect the amount the discharge is cooled while traversing the canal, with colder air temperatures and higher wind speeds expected to increase the cooling experienced prior to mixing with the ambient river flow.

To determine the average temperature increase of the discharge flow over the ambient river temperature, historical temperature data from sampling station S0 (where the discharge canal flows into the Merrimack River) were compared to the corresponding N10 river temperature data, and the average temperature increase was calculated (Reference 6.6). To do this, a data set of 20 years of daily average temperatures was initially considered. This data set was then filtered for days where both Unit 1 and Unit 2 were simultaneously operating at 90% of their rated generation capacity or greater. Only days where both units were simultaneously operating at 90% capacity or greater were considered so that the cases analyzed would represent true "plant on" scenarios, with the plant operating at approximately its design capacity. Once the data set was filtered, the average temperature difference between the upstream ambient river temperature (N10) and the effluent temperature at the mouth of the discharge canal (S0) was calculated. This temperature difference inherently captures both the increase in fluid temperature due to the plant's heat load and the cooling experienced as the fluid traveled through the discharge canal. The average temperature rise was calculated to be 20.6°F.

It should be noted that the data set used to calculate the average temperature rise of 20.6°F only included the months April through November, due to the temperature probes at N10 being removed during the winter to avoid potential damage from icing (see Section 3.1). As described above, air temperature has an impact on the amount of cooling experienced as the discharge flow travels through the discharge canal. It is expected that the cooler winter-time air temperatures would provide more cooling to the effluent in the canal than the warmer summer-time temperatures. Therefore, by considering data for the months April through November, the average temperature increase between N10 and S0 of 20.6°F is likely conservatively higher than the temperature increase that would actually be experienced if both units were to be operating at design conditions during the winter months evaluated in the four CFD cases.

When the average temperature increase of 20.6°F between N10 and S0 is considered in conjunction with the assumed ambient river temperature of 33°F, the discharge temperature then becomes 53.6°F for all four cases. The combination of using an average temperature increase that is conservatively high for the winter months of interest and using the design discharge flow rates for both units (Section 3.2) creates cases which model what is expected to be the most significant thermal plume scenario during each of the winter months of interest.

4 Model Description

To characterize the thermal plume for the four winter months of interest, first a physical model of the Merrimack River and Merrimack Station discharge canal was constructed. Once the model was constructed, it was imported into the CFD software and a computational mesh was built to accurately resolve the model to the level of detail required to characterize the plume. Next, the relevant physical models (i.e. gravity, heat transfer, viscosity and turbulence, etc.) and boundary conditions were applied to the model. Finally, the CFD model was run for four different cases, varying the case-dependent model parameters described in Section 2 to characterize the plume for the "plant on" scenario in the months December, January, February, and March.

4.1 3-Dimensional Computer Aided Design (CAD) Model

The first step in performing the CFD analysis was to construct a 3-dimensional CAD model of the Merrimack Station discharge canal and the Merrimack River in the vicinity of the discharge canal. In order to develop this 3-dimensional model and accurately capture the geometry of the river and discharge canal banks, detailed bathymetry data of the discharge canal and the Merrimack River was required. The raw bathymetry data in these areas of interest was provided by Normandeau in Reference 6.7. This raw data was then processed using a geographic information system (GIS) software to capture the river bed geometry data in a format that could be imported into the CAD software. Once the bathymetry data was imported into the CAD software, the discharge canal and riverbed geometry files were exported in a stereolithography (STL) format, which can be imported directly into the CFD software. The discharge canal and river bed geometries were captured in separate STL files so that different initial properties could be assigned to each. For example, the initial temperature of the discharge canal was set to 53.6°F, equal to the effluent discharge temperature, and the initial temperature of the river bed was set to 33°F, equal to the ambient fluid temperature. To capture the heat transfer between the fluid and the river geometry, both the discharge canal and river bed STL files were assigned a thermal conductivity of 1.39 Btu/(hr·ft·°F) (Reference 6.12) and a surface roughness of 0.0164 feet. The surface roughness was calculated based on the following equation (Reference 6.12, Page 469):

$$k_s = 2.5 * d_{50}$$

Where k_s is the surface roughness and d_{50} is the grain diameter where 50% of the material by weight is finer. The Merrimack River in the vicinity of the Station has been reported to be coarse sand, and therefore a d_{50} grain diameter of 2 mm (0.00656 feet) is assumed (Reference 6.12, Appendix C). Using the equation above, this yields a surface roughness of 0.0164 feet.

A plan view of the discharge canal and river bed geometry files is shown in Figure 1 below.

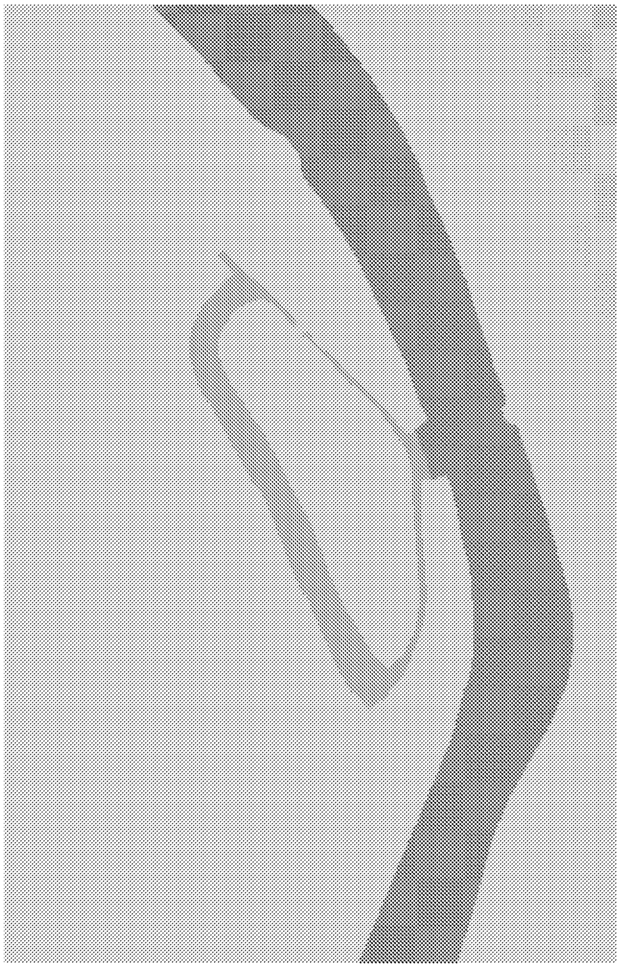

Figure 1: Discharge Canal and Merrimack River STL Files

4.2 Computational Mesh

A single rectangular mesh was defined in the CFD model to characterize the thermal plume. The mesh included a total of 2,624,000 cells, with 400 cells in the X-direction (east to west), 820 cells in the Y-direction (north to south), and 8 cells in the Z-direction (vertical direction). The maximum cell sizes in the x, y, and z directions were 2.5’, 3.0’ and 1.5’, respectively.

A hydraulic diameter is a characteristic length used to calculate Reynolds numbers for flows in non-circular pipes, such as flows through square ducts or open channels. For open channel flow, the hydraulic diameter is a function of the area and wetted perimeter of the fluid flow. In order to accurately model the mixing of the river and effluent flows, the north end of the mesh was positioned approximately 15 hydraulic diameters upstream of the mouth of the discharge canal, far enough that the ambient river flow would have ample time to fully develop the flow profile before it met the discharge flow. The south end of the mesh was positioned at approximately the same location downstream as sampling station S4, so that the thermal plume could be characterized at that location of interest. As shown in the figure below, the east end of the mesh was positioned so that the entire river was encompassed and the west end was positioned to capture the relevant portion of the discharge canal.

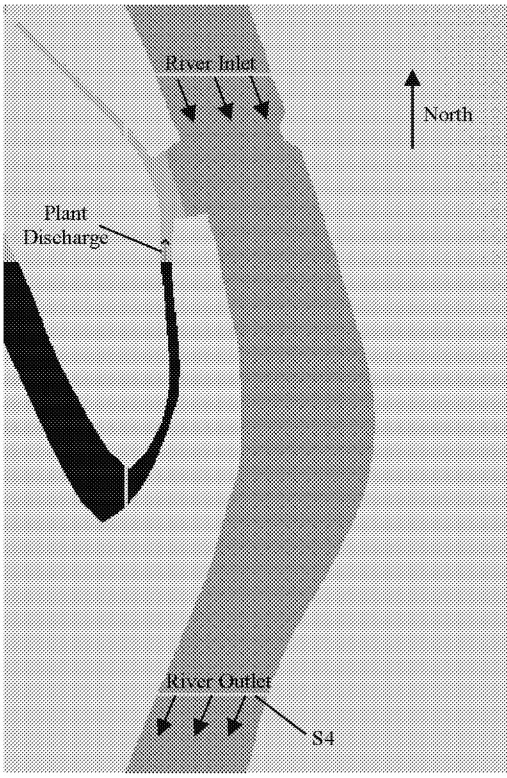

Figure 2: Mesh Configuration

In the CFD model, a portion of the discharge canal was filled with a solid filler block, shown in black in Figure 2. The model was configured such the effluent discharged from the northern-most end of the black filler block and into the discharge canal, initially flowing north until it mixed with the ambient river flowing the opposite direction. The purpose of filling a portion of the discharge canal and starting the effluent discharge flow at this location was to minimize the heat transfer from the effluent flow that occurred prior to mixing with the ambient river flow, ensuring that the effluent exited the discharge canal at the correct temperature (see Section 3.3). Additionally, modeling the effluent discharge in this manner significantly reduced the complexity of the model and the computational time required to solve it. The discharge point was set approximately 12 hydraulic diameters back from the mouth of the discharge canal, far enough that the flow had ample time to create a fully developed flow profile prior to mixing with the ambient river flow.

4.3 Physical Models

Within the CFD model, various physical models were utilized to accurately capture the appropriate thermal and hydraulic effects. The significant physical models that were used in the thermal plume CFD model are described below.

Gravity and Non-Inertial Reference Frame

In order for the CFD model to accurately depict reality, the gravity physical model was activated. The gravity force was set to 32.17 ft/s^2 in the negative Z-direction.

Heat Transfer

The heat transfer physical model was activated to capture the various thermal effects within the CFD model. The full energy equation was used to model fluid-to-solid heat transfer, so that the temperature profile of both the fluid and the solid discharge canal and river bed were calculated for each time-step. The viscous heating option was also activated. The primary areas of heat transfer within the model include the heat transferred during the mixing of the effluent and ambient river flows, the heat transferred between the thermal plume and the river banks/bottom, and the heat transferred between the fluid in the river and the ambient air.

Density Evaluation

The density evaluation physical model was activated so that the buoyancy of the thermal plume (created by the temperature difference between the heated effluent and the cooler ambient water) was captured in the CFD model. The density was evaluated as a function of temperature, and volumetric thermal expansion was included.

Viscosity and Turbulence

The viscosity and turbulence physical model was activated to capture any areas of turbulent flow within the model. Additionally, this physical model allowed the viscous effects between the fluid and the river bed bottom to be captured. Several different turbulence modeling approaches can be selected for a FLOW-3D® calculation. The approaches are (ranging from least to most sophisticated):

- Prandtl mixing length
- Turbulent energy model
- Two-equation k-ε model
- Renormalized group theory (RNG) model
- Large eddy simulation model

The RNG turbulence model was judged to be the most appropriate for this CFD analysis due to the large spectrum of length scales that exist in the river model. The RNG approach applies statistical methods in a derivation of the averaged equations for turbulence quantities (such as turbulent kinetic energy and its dissipation rate). RNG-based turbulence schemes rely less of empirical constants while setting a framework for the derivation of a range of models at different scales. Sensitivity calculations have shown that FLOW-3D® calculations utilizing the more sophisticated turbulence models (the RNG model included) give results that differ significantly from calculations utilizing the less sophisticated models. Differences in results between calculations made with the more sophisticated models have been shown to be slight.

The other options within the viscosity and turbulence model that were selected include the viscous flow option, the "No-slip or partial slip" wall shear boundary condition option, and the viscous heating option.

Wind

The wind physical model was activated to capture the convective heat transfer between the fluid flow and the ambient air, as well as any mixing effects that the wind had on the thermal plume. The constant wind option was selected, and the X-velocity and Y-velocity components of the wind for each case were determined from the wind speeds and wind directions presented in Section 2. The void for each case (volume within the CFD model not occupied by the fluid) was set to the air temperatures presented in Section 2.

4.4 Boundary Conditions

In CFD modeling, boundary conditions are used to define the inputs of the simulation model, such as set rate of fluid flow into the model or a pressure differential used to drive flow. Boundary conditions are set at the minimum and maximum bounds of the x, y, and z planes. The minimum z boundary condition (discharge canal and river bed bottoms) was set to a wall boundary with a temperature of 33°F, equal to the assumed ambient river temperature. A wall roughness of 0.0164 feet was applied to this boundary condition to capture the viscous mixing and heat transfer that occurred at the interface of the fluid and river bottom. The maximum z boundary condition (above the water level) was set as a pressure boundary to model a constant atmospheric temperature and pressure above the free surface. The maximum y boundary (north, upstream of the discharge canal mouth) was set as a volumetric flow boundary, with the flow rates presented in Section 2 used for the various cases. For all four cases, the flow through this boundary condition was set to a temperature of 33°F. The direction of the flow was set approximately parallel to the river banks at the mesh boundary so that the flow could quickly become fully developed. The minimum y boundary (south, downstream of the discharge canal mouth) was set as an outflow boundary so that the flow could exit the model as needed. The maximum and minimum x boundaries were both set as symmetry boundaries.

4.5 Modeling of the Mass Source

As described earlier, the model was configured such that the effluent discharged through only a portion of the discharge canal to ensure that the effluent was the correct temperature at the mouth of the discharge canal (S0) and to reduce the overall complexity of the model. A rectangular mass source was placed at the edge of the solid part used to fill a portion of the discharge canal to provide a discharge source into the canal. The mass source was partially embedded in the solid filler block, and a "cap" was placed on top of the mass source to ensure that water only discharged from the northern most face, directly into the discharge canal. The mass source's placement (orange rectangle) in the discharge canal is shown Figure 3. To model the plant's discharge, the mass source was assigned a constant volumetric rate of 443.4 cfs (see Section 3.2) at a temperature of 53.6°F (see Section 3.3).

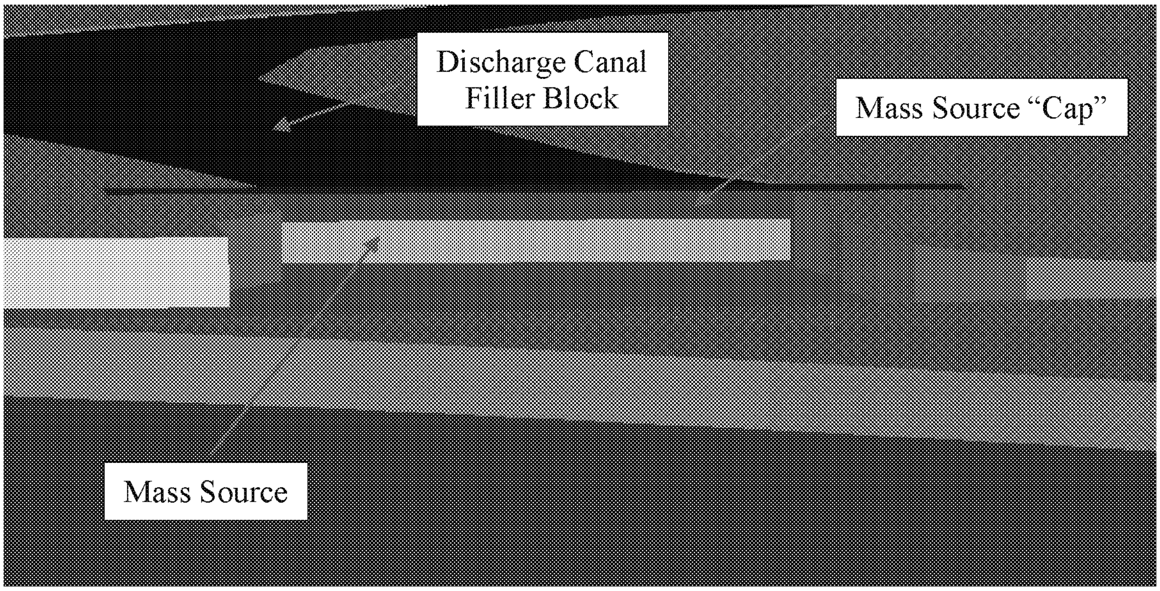

Figure 3: Mass Source Location

4.6 Calculation Termination

For all four cases, the CFD model was run long enough for steady-state conditions to develop and for the results to remain constant over time so that the true thermal plume could be characterized. Calculated mean kinetic energy in the model was used as the indicator for determining steady state. When this parameter stops changing, it is a good indication that steady-state has been achieved and the results will remain the same. The steady state criterion was set as a 1% change or less in the mean kinetic energy over a 45-minute period within the simulation (i.e. 45 minutes of flow within the model).

All four cases met the steady state criteria listed above except for Case 3, which evaluated the month of February. Rather than the standard steady state solution, where the mean kinetic energy stabilized and changed 1% or less over a 45-minute period, the February case instead reached a periodic steady state solution. Due to the relatively low ambient river flow in February

(3,158 cfs), the plant discharge interacted with the river flow in a manner that allowed the plume to build-up near the mouth of the discharge and eventually release and travel downstream. Once one build-up released and flowed downstream, a new plume build-up began to occur. This process occurred consistently, with an average period of approximately 75 minutes. Although this phenomenon prevented the mean kinetic energy from meeting the steady-state criteria used for the other cases, the model was run long enough to determine that this periodic steady state had been achieved.

5 Results

A total of four different CFD cases were modeled using the parameters described in Sections 2 and 3. These four cases were developed to characterize the thermal plume downstream of the plant in the winter months of December, January, February, and March with both units operating at design conditions. The results of these four models were processed in the CFD post-processing software EnSight, and are presented in Sections 5.1 through 5.4. Note that although the models were developed and run using English units (i.e. °F), all temperatures were converted to °C during post-processing to allow for ease of use in AST's biological evaluation (Reference 6.1).

5.1 Case 1 – December

The December CFD case was characterized by relatively high ambient river flow (6,030 cfs) and relatively warm ambient air (31.5°F). The thermal plume at the water surface for this case is shown in Figure 4 and was observed to be attached to the western river bank and relatively thin, taking up a small overall percentage of the river. Although the temperature of the plume dissipates as it travels downstream, a small temperature increase over ambient was observed downstream of the discharge at sampling station S4.

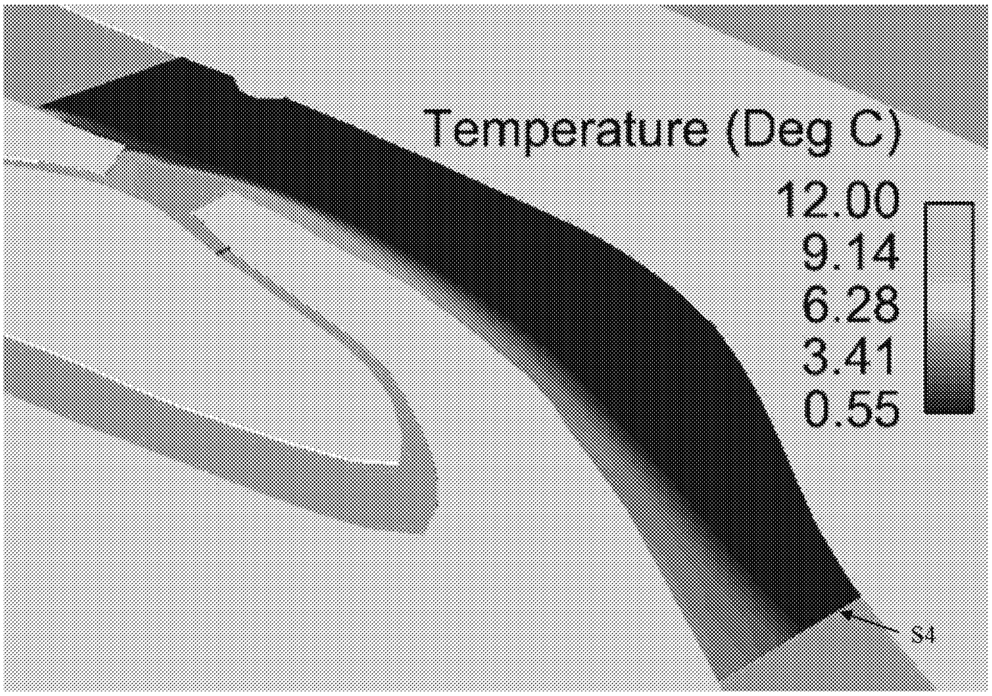

Figure 4: Isometric View of December Results

A cross-sectional view of the thermal plume at S4 is provided in Figure 5 for the December case. The cross-sectional view starts from the western bank on the left side of the graph and traverses the width the river to the eastern bank, shown on the far-right side of the graph. The x-axis shows the distance from the western bank, in feet. Black temperature contours lines for the temperatures 3.77°C, 2.00°C, and 1.63°C are shown on the output, and the 2.00°C contour is designated by white shading. The maximum water temperature at the riverbed is approximately 4.85°C, and, as shown in the figure below, approximately 56% of the river bottom remains at a temperature below 2°C.

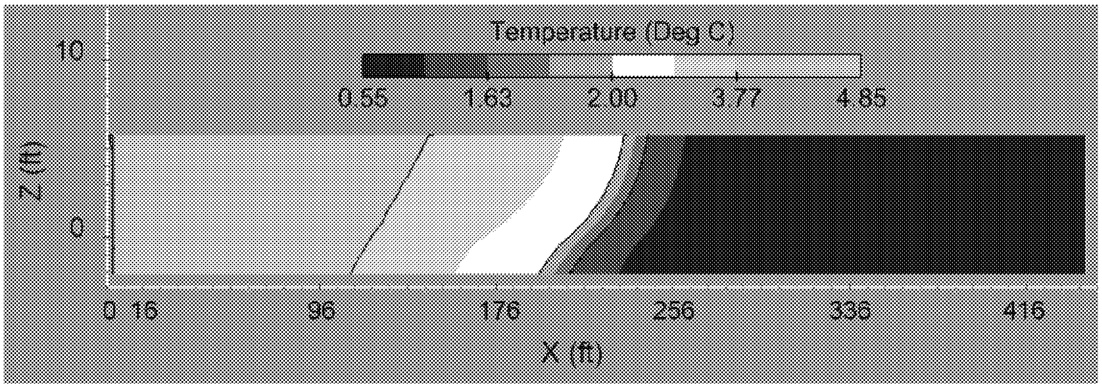

Figure 5: Cross-Sectional View of December Results at S4

Note that although the contours shown in the figure above are displayed in a relatively coarse gradient, the temperature results are calculated for every cell within the CFD model. With a total of 400 cells in the X-direction, the computational mesh was sufficiently fine to provide a detailed resolution of the model and an accurate characterization of the thermal plume. The contours in Figure 5 are shown in a coarser gradient for the purpose of simplifying the presentation of the model results and allowing them to be easily interpreted.

5.2 Case 2 – January

The January CFD case was characterized by relatively low ambient river flow (4,405 cfs) and relatively cold ambient air (23.9°F). The thermal plume at the water surface for this case is shown in Figure 6 and was observed to be attached to the western river bank, somewhat irregular as it traveled downstream, and relatively thin, taking up a small overall percentage of the river. Although the temperature of the plume dissipates as it travels downstream, a small temperature increase over ambient was observed downstream of the discharge at sampling station S4.

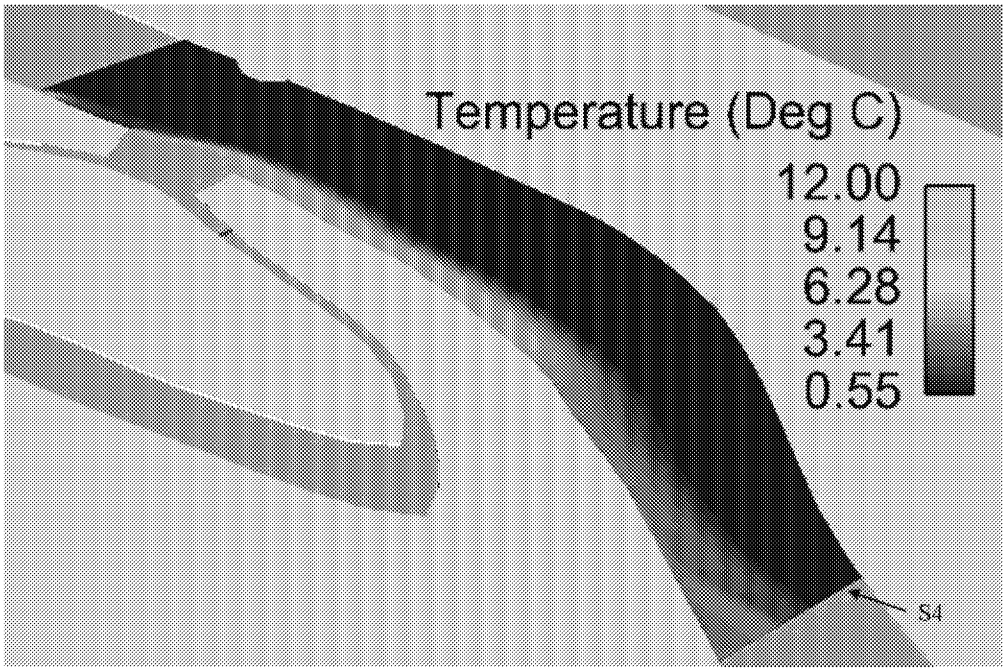

Figure 6: Isometric View of January Results

A cross-sectional view of the thermal plume at S4 is provided in Figure 7 for the January case. The cross-sectional view starts from the western bank on the left side of the graph and traverses the width the river to the eastern bank, shown on the far-right side of the graph. The x-axis shows the distance from the western bank, in feet. Black temperature contours lines for the temperatures 3.77°C, 2.00°C, and 1.63°C are shown on the output, and the 2.00°C contour is designated by white shading. The maximum water temperature at the riverbed is approximately 4.85°C, and, as shown in the figure below, approximately 55% of the river bottom remains at a temperature below 2°C.

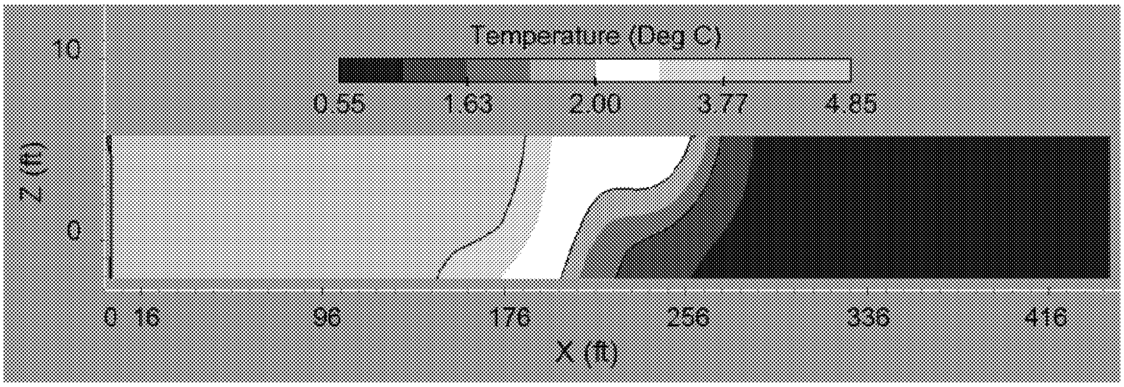

Figure 7: Cross-Sectional View of January Results at S4

Note that although the contours shown in the figure above are displayed in a relatively coarse gradient, the temperature results are calculated for every cell within the CFD model. With a total of 400 cells in the X-direction, the computational mesh was sufficiently fine to provide a detailed resolution of the model and an accurate characterization of the thermal plume. The contours in Figure 7 are shown in a coarser gradient for the purpose of simplifying the presentation of the model results and allowing them to be easily interpreted.

5.3 Case 3 – February

The February CFD case was characterized by relatively low ambient river flow (3,158 cfs) and relatively cold ambient air (24.2°F). The thermal plume at the water surface for this case is shown in Figure 8 and was observed to be attached to the western river bank and slightly irregular as it traveled downstream. Although the temperature of the plume dissipates as it traveled downstream, a small temperature increase over ambient was observed downstream of the discharge at sampling station S4.

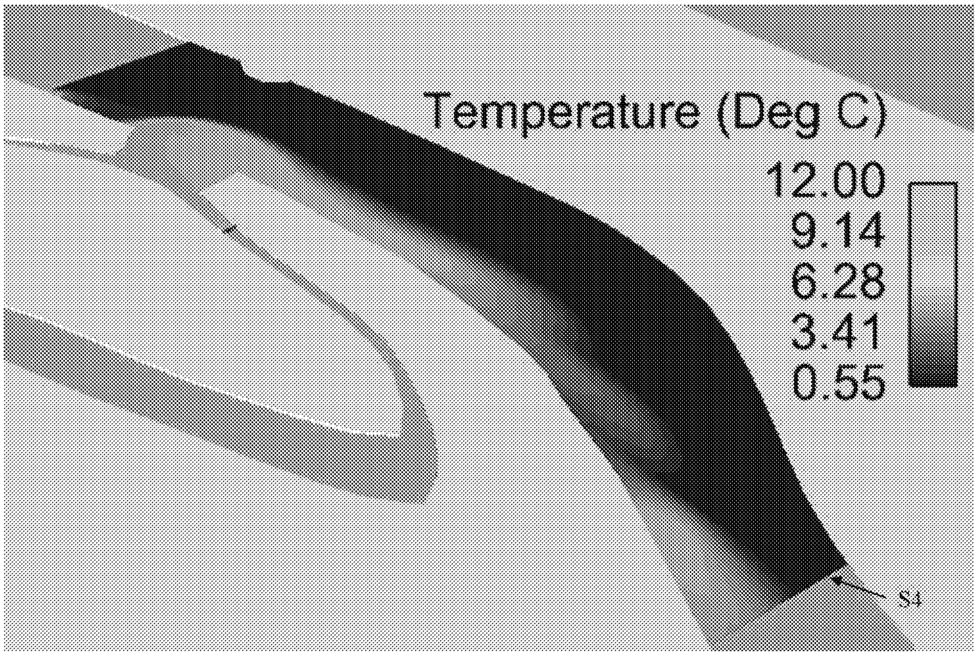

Figure 8: Isometric View of February Results

A cross-sectional view of the thermal plume at S4 is provided in Figure 9 for the February case. The cross-sectional view starts from the western bank on the left side of the graph and traverses the width the river to the eastern bank, shown on the far-right side of the graph. The x-axis shows the distance from the western bank, in feet. Black temperature contours lines for the temperatures 4.34°C, 2.00°C, and 1.81°C are shown on the output, and the 2.00°C contour is designated by white shading. The maximum water temperature at the riverbed is approximately 4.34°C, and, as shown in the figure below, approximately 52% of the river bottom remains at a temperature below 2°C.

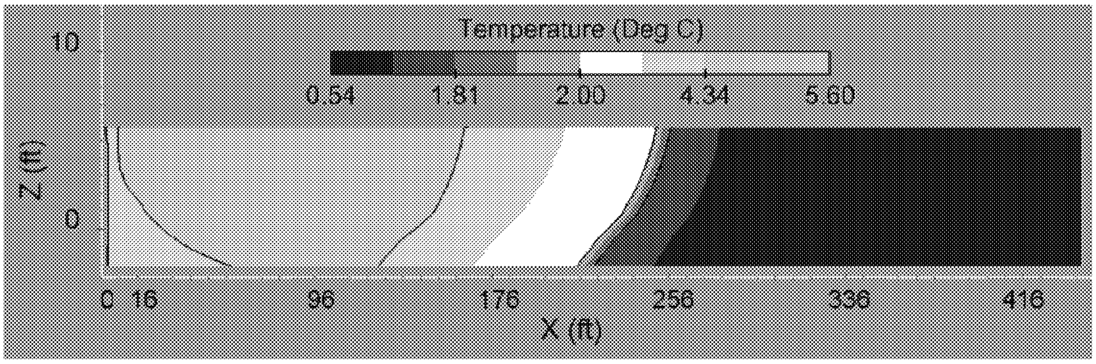

Figure 9: Cross-Sectional View of February Results at S4

Note that although the contours shown in the figure above are displayed in a relatively coarse gradient, the temperature results are calculated for every cell within the CFD model. With a total of 400 cells in the X-direction, the computational mesh was sufficiently fine to provide a detailed resolution of the model and an accurate characterization of the thermal plume. The contours in Figure 9 are shown in a coarser gradient for the purpose of simplifying the presentation of the model results and allowing them to be easily interpreted.

5.4 Case 4 – March

The March CFD case was characterized by relatively high ambient river flow (6,545 cfs) and relatively warm ambient air (33.9°F). The thermal plume at the water surface for this case is shown in Figure 10 and was observed to be attached to the western river bank and relatively thin, taking up a small overall percentage of the river. Although the temperature of the plume dissipates as it travels downstream, a small temperature increase over ambient was observed downstream of the discharge at sampling station S4.

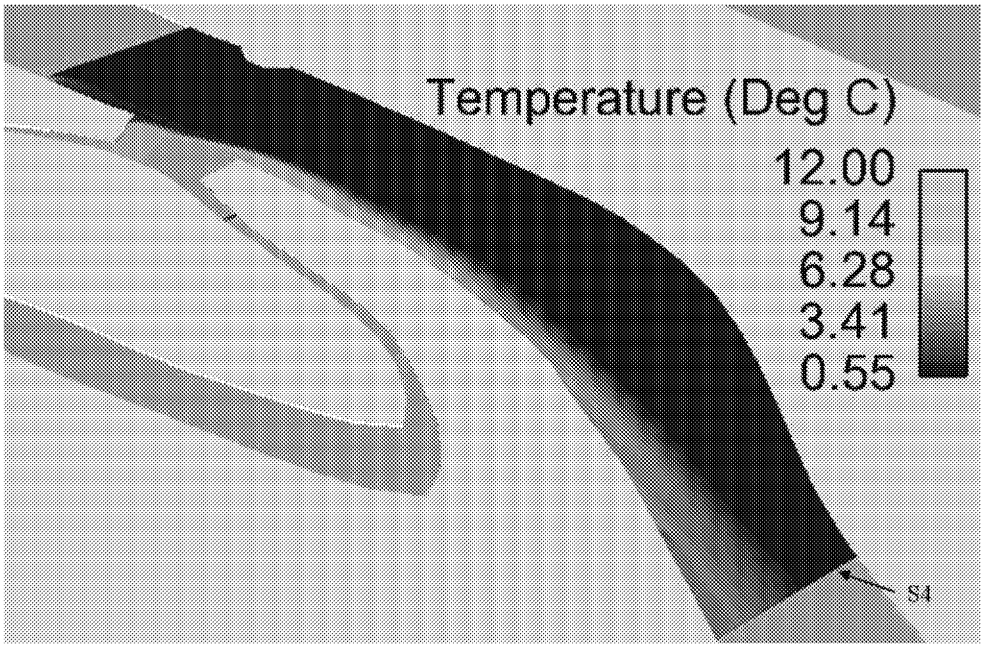

Figure 10: Isometric View of March Results

A cross-sectional view of the thermal plume at S4 is provided in Figure 11 for the March case. The cross-sectional view starts from the western bank on the left side of the graph and traverses the width the river to the eastern bank, shown on the far-right side of the graph. The x-axis shows the distance from the western bank, in feet. Black temperature contours lines for the temperatures 3.83°C, 2.00°C, and 1.64°C are shown on the output, and the 2.00°C contour is designated by white shading. The maximum water temperature at the riverbed is approximately 3.83°C, and, as shown in the figure below, approximately 60% of the river bottom remains at a temperature below 2°C.

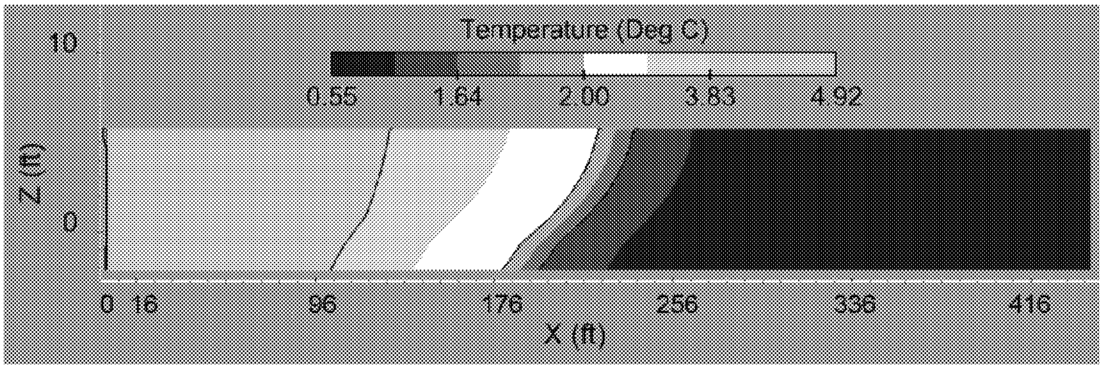

Figure 11: Cross-Sectional View of March Results at S4

Note that although the contours shown in the figure above are displayed in a relatively coarse gradient, the temperature results are calculated for every cell within the CFD model. With a total of 400 cells in the X-direction, the computational mesh was sufficiently fine to provide a detailed resolution of the model and an accurate characterization of the thermal plume. The contours in Figure 11 are shown in a coarser gradient for the purpose of simplifying the presentation of the model results and allowing them to be easily interpreted.

5.5 Discussion of Results

As described in Section 3, the ambient river temperature, discharge flow rate, and discharge temperature remained the same for all four cases. These parameters remained constant in order to model a “plant on” scenario, with both units operating at full design conditions, for each winter month of interest. Therefore, the parameters that were changed from case to case were the ambient river flow rate, ambient air temperature, and wind speed and direction.

The ambient river flow rate was the largest driver in the differences among the results of the four cases. Although the air temperature and wind properties did have an impact on the results, the impact of these parameters was secondary compared to the impact of the ambient river flow.

As shown in Section 2, December and March had the highest ambient flows at 6,030 cfs and 6,545 cfs, respectively. For these two cases, the relatively high ambient river flows had the effect of "pulling" the plume downstream, creating a relatively thin plume that was attached to the western bank. The relatively high ambient river flows also tended to dominate the mixing of the plume, rather than buoyancy effects created by the temperature differential, creating a well-mixed plume with little stratification in the water column.

In comparison, February had a relatively low ambient river flow (3,158 cfs) or less than half of the river flow in March. This low river flow allowed the temperature-driven buoyancy effects to play a larger role in the mixing of the plume, creating a more distinct stratification in the water column. This stratification showed the warmer, less dense portion of the plume rising towards the river surface. As described in Section 4.6, the low ambient river flow also created a periodic plume discharge pattern, with the plume building up at the mouth of the discharge canal and then releasing downstream at regular intervals.

For all cases, the thermal plume was observed to be attached to the western bank of the river, and was always more narrow at the river bottom than at the water surface. As shown by the contour lines, the 2°C threshold at the river bottom ranged from approximately 178 feet to 214 feet from the western bank. For all cases, the 2°C threshold was met well before the central S4 clam sampling location, which is 246 feet from the western bank (Reference 6.9).

5.6 Conclusion

This CFD analysis was performed to characterize the thermal plume in the Merrimack River for the winter months of December, January, February, and March with both units at the Station operating at design conditions. To do this, average ambient conditions (river flow, air temperature, wind speed and direction) were used to develop four different CFD cases. Each of the four cases was run until it reached steady-state, and then the results were post-processed to provide a characterization of the thermal plume. This analysis is provided for use as a screening tool to determine if any of the evaluated scenarios require further examination. These results are valid to inform the biological evaluations presented in AST's report regarding the Asian clam in the Hooksett Pool (Reference 6.1).

6 References

6.1 Asian clam and Lack of Evidence for Appreciable Harm to the BIP in Hooksett Pool, Merrimack River, New Hampshire, AST Environmental, December 2017.

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6.4 Local Climatological Data (LCD) Dataset Documentation, NOAA Database Order ID #1062636.

6.5 Wedgewire Half Screen Technical Memo, Enercon Services, Inc., December 2016.

6.6 Merrimack Station Daily N10 and S0 Temperature Data spreadsheet, provided by PSNH on 11/17/16.

6.7 Merrimack River Bathymetry Data, provided by Normandeau Associates, Inc. on 10/15/16.

6.8 CORMIX Thermal Plume Modeling Technical Report, Enercon Services, Inc., December 2016.

6.9 S4 Asian Sampling Locations GPS Coordinates spreadsheet, provided by AST on 9/21/17.

6.10 Markle, J. M., R. A. Schincariol, J. H. Sass, and J. W. Molson. 2006. Characterizing the Two-Dimensional Thermal Conductivity Distribution in a Sand and Gravel Aquifer. Soil Sci. Soc. Am. J. 70:1281-1294. doi:10.2136/sssaj2005.0293.

6.11 River Flow 2012, Rafael Murillo Munoz, CRC Press, October 5, 2012.

6.12 ISO 16448-1, Geotechnical Investigation and Testing – Identification and Classification of Soil – Part 1: Identification and Description, International Organization for Standardization.